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RESEARCH MEMORANDUM

A PRELIMINARY INVESTIGATION OF WALL EFFECTS ON
PRESSURE-INFLAMMABILITY LIMITS OF
PROPANE-AIR MIXTURES

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RESEARCH MEMORANDUMA PRELIMINARY INVESTIGATION OF WALL EFFECTS ON
PRESSURE-INFLAMMABILITY LIMITS OF
PROPANE-AIR MIXTURES

By Frank E. Belles

SUMMARY

A preliminary investigation was made of the wall effects on the pressure-inflammability limits for flame propagation in propane-air mixtures. Pressure limits were experimentally determined for: (1) quiescent mixtures in glass tubes of different diameters (51, 38, 32, 25, and 18 mm); and (2) turbulent mixtures in a glass tube of 51-millimeter diameter containing a rotor.

The pressure-inflammability limits depended directly on the relative tube-wall area, as expressed by the surface-volume ratio. The minimum pressure for flame propagation increased with diminishing tube diameter (greater relative wall area) and with turbulence of a type that effectively increased the wall area.

INTRODUCTION

The limiting pressures for combustion of homogeneous gas mixtures, measured under static conditions in glass tubes, are of the order of 30 millimeters of mercury or less. The altitude operational limits of turbojet engines, on the other hand, occur at combustion-chamber pressures corresponding to pressures much higher than 30 millimeters of mercury. This penalty on the engine combustion process is evidently due to the differences in the engine and static-tube test conditions, such as the effects of gas-stream velocity and turbulence, geometrical configuration, the atomization, vaporization, and mixing of the liquid fuels.

In order to assess the magnitude of the effects of geometrical configuration and one type of turbulence on the pressure-inflammability limits, additional conditions were imposed on the static-tube type of experiment. In one case, pressure limits were determined for quiescent mixtures in tubes of different diameters; in the other case, limits

were determined for gas mixtures stirred by a rotor. The object of this preliminary investigation was to partly bridge the gap between fundamental laboratory experiments and applied engine research.

The pressure-inflammability limit of a given fuel-air mixture, as defined in this investigation, is the lowest pressure at which a flame, when ignited at one end of a closed tube, will propagate to the opposite end of the tube. Propagation will evidently depend in part on the diameter and length of the tube and on the direction in which the flame must move. Coward and Jones (reference 1), after consideration of the concentration limits of inflammability at atmospheric pressure as determined by many investigators, concluded that the limits were independent of tube diameter and length if the tube was at least 5 centimeters in diameter and 4 feet in length. In addition, they recommended that the method of determining the limits at atmospheric pressure be standardized by choosing vertically upward flame propagation.

For inflammability limits determined at pressures less than atmospheric, very limited data are available on the effect of tube diameter. Elston and Laffitte (reference 2) indicate that the pressure limit does depend upon tube diameter in the case of methane-air mixtures. Holm (reference 3) points out that, theoretically, the minimum pressure for flame propagation in a tube should be inversely proportional to the tube radius. This theory is equivalent to saying that the minimum pressure for propagation should be directly proportional to the surface-volume ratio S/V inasmuch as S/V is proportional to the reciprocal of the tube radius in the case of a cylindrical tube.

In the present investigation conducted at the NACA Lewis laboratory, pressure-inflammability limits were determined for quiescent mixtures in cylindrical glass tubes with diameters of 51, 38, 32, 25, and 18 millimeters in order to determine the magnitude of the geometrical-configuration effect as measured by the surface-volume ratio.

Several investigators (reference 1) have reported that severe turbulence has an adverse effect on combustion at atmospheric pressure, as revealed by difficulty in the ignition and the propagation of flame. Although combustion in turbulent mixtures is a complex phenomenon and must be influenced by the scale, the intensity, and the type of turbulence prevailing, it is not difficult to conceive of a turbulent

condition that would increase the contact of the combustible mixture with the walls. Such a condition was qualitatively studied in the second phase of this investigation, in which the pressure-inflammability limits of propane-air mixtures were measured in a 2-foot glass tube 51 millimeters in diameter containing a longitudinal rotor for agitating the propane mixture.

APPARATUS AND PROCEDURE

Preparation of Propane-Air Mixtures

The propane-air mixtures were prepared for both the quiescent and the turbulent experiments by the method of partial pressures, assuming ideal-gas behavior. A 47-liter carboy was evacuated and propane of 99-mole-percent minimum purity was admitted until its pressure, as read on an absolute manometer, corresponded to the desired percentage of atmospheric pressure. Undried air was then admitted to bring the carboy to atmospheric pressure. The propane and the air were mixed by allowing them to stand overnight in the closed carboy, or by stirring them for 30 minutes by means of motor-driven vanes sealed into the carboy. The pressure-inflammability limit of a given propane-air mixture was found to be the same when the mixture was prepared by either method.

Limits of Quiescent Mixtures

The flame tubes used for the determination of the pressure limits of quiescent mixtures were composed of two parts assembled vertically. The lower part was an ignition section of 51-millimeter glass tubing 10 inches long with two spark electrodes sealed through its side walls (fig. 1). The interchangeable glass tubes in which the limits were to be measured were mounted above the ignition section and joined to it with rubber stoppers. Five 4-foot tubes with diameters of 51, 38, 32, 25, and 18 millimeters were used in this investigation. The large-diameter ignition section was used in order to avoid the probable effects of tube diameter on the ignition of the mixtures.

During a run the two-piece flame tube, tightly clamped together, was evacuated. The propane-air mixture from the storage carboy was then admitted to the desired pressure, as measured on a differential manometer. When the pressure within the carboy was lower than the desired pressure, a Toepler pump was used to transfer the mixture from the carboy to the flame tube. Approximately 1 minute was allowed for

the mixture to become quiescent. The mixture was then ignited by passing the spark from a 10,000-volt ignition transformer between the electrodes. The criterion for propagation was flame travel through the complete length of the upper tube. The pressure limit for the mixture in each tube was fixed by repeated trials until a pressure was reached at which the flame was extinguished before it reached the upper end of the tube. The reproducibility of the pressure limit was ± 3 millimeters of mercury. For a given mixture composition, limits were measured in all the tubes with the same charge of fuel-air mixture in the carboy. This procedure was necessary because the fuel system for these preliminary studies was not designed for great accuracy in the preparation of mixtures.

Difficulty was experienced with the narrower flame tubes in obtaining reproducible pressure limits for very lean mixtures and for mixtures richer than stoichiometric; consequently, the range of mixture compositions that could be studied in the small-diameter tubes was sharply limited.

Limits of Turbulent Mixtures

The flame tube used for the determination of the limits of turbulent mixtures also was composed of two lengths of glass tubing, but so arranged that the axis of the setup was horizontal rather than vertical. One 51-millimeter tube was employed. The ignition section, 10 inches in length, was fitted with two spark electrodes. The propagation test section was 2 feet in length and contained an axial, four-vaned rotor of the same length machined from aluminum. The rotor was supported by bearing struts (fig. 2), and was turned by a variable-speed motor operating through a stuffing box. A separate ignition section was used in this apparatus to eliminate any effect the turbulent motion of the gas might have upon its ignition (reference 4). Smoke tests showed that the rotor did not agitate the gas in the ignition section.

During a run, the apparatus was evacuated and propane-air mixture from the carboy was admitted to the desired pressure. The criterion for propagation and method of arriving at the pressure limit have been described. The limits were measured for a given mixture composition with the rotor stationary (gas quiescent) and with the rotor turning at 1850 rpm. Two limits were also obtained with a rotor speed of 850 rpm. Despite the fact that the rotor shaft passed through a stuffing box, it was possible to make the system virtually leak proof over a period of 10 to 15 minutes, far longer than the time required for each test.

Reproducibility of the pressure limits in this apparatus was ± 5 millimeters of mercury, except in the region noted in figure 7.

RESULTS AND DISCUSSION

Effect of Tube Diameter

Figure 3 presents curves of pressure-inflammability limit plotted against volume percent of propane in air for the five tube diameters studied. It can be seen that the composition range of inflammability at atmospheric pressure is the same for all the tubes, within the limits of accuracy with which fuel-air mixtures could be prepared. This observation is in agreement with reference 1, which points out that at atmospheric pressure, the effect of tube diameter is not pronounced for diameters greater than 10 millimeters. At lower pressures, however, the rich and lean mixture limits begin to converge; at any given low pressure, the smaller the tube diameter, the greater the convergence. The minimum pressure at which flame propagation can be obtained also varies inversely with the tube diameter.

Geometrical-configuration effect, as expressed by the surface-volume ratio, is shown in figure 4 to have a direct effect on pressure-inflammability limits. This fact suggests that the convergence of rich and lean mixture limits and the increase in the minimum pressure for propagation, as the tube diameter is decreased, are wall effects alone. These data, however, are insufficient to indicate the mechanism of the wall effect.

The roughness of these data does not warrant an extrapolation of the curves in figure 4 to a minimum pressure for flame propagation in any tube; but the trend of the curves indicates a very low minimum pressure at $S/V = 0.05$ to 0.04 , corresponding to tube diameters of 80 to 100 millimeters.

Nagai (reference 5) shows that portions of the fuel-lean sides of pressure-limit curves such as those in figure 3 can be expressed linearly

$$C = D (1/P) + B \quad (1)$$

where

C concentration of fuel in air

D slope of line

P pressure limit for mixture of fuel concentration C

B constant having dimensions of concentration

If P is large, the term $D (1/P)$ becomes negligible, and

$$C \rightarrow B \quad (2)$$

Thus, for the lean limit at atmospheric pressure when $P = 760$ millimeters of mercury, equation (2) is approximately correct, and the lean-limit mixture composition should be the same in tubes for all diameters. The fact that this statement is true for all but very narrow tubes has already been pointed out in reference 1.

Application of this analysis to data on the pressure limits of various lean fuel-air mixtures, in tubes of different diameters, should yield a series of straight lines having different slopes. This procedure has been followed for some of the data obtained in this investigation. Reciprocals of the pressure limits taken from the curves in figure 3 are plotted against concentration in figure 5. If the observed effects of tube diameter on pressure limit are due to increased wall effect with smaller diameter, the slope (D , equation (1)) should be inversely proportional to tube diameter because the slope is the factor that takes these effects into account. Figure 5 shows that this prediction is reasonably well borne out.

Effect of Turbulence

Results of the experiments conducted in the horizontal flame tube containing a rotor are presented in figure 6 as pressure-inflammability limit against volume percent of propane in air. The limits of quiescent mixtures were determined in this apparatus as a basis for comparison.

When the tube was filled with smoke and the rotor turned, the air in the ignition section, into which the rotor did not extend, remained quiet. This observation indicated that the rotor did not move the gas longitudinally, but rather caused it to scrub the walls of the ignition section.

Under these conditions of turbulence, the effect of the tube walls on the pressure limits should be greater than in the quiescent condition. From the experiments on pressure limits in tubes of various diameters, it may be predicted that this type of turbulence should result in a narrower inflammability range and a higher minimum

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pressure for flame propagation. The experimental pressure-limit curves (fig. 6) demonstrate the anticipated trends. The points taken with the rotor turning at 1850 rpm show a marked deviation from the results obtained with the mixture quiescent, particularly on the lean side of the minimum. At a rotor speed of 850 rpm, the turbulence created was not severe enough to affect the two points obtained at this speed to any great degree. Figure 6 shows that the inflammability range is much different for quiescent mixtures in this apparatus than in the vertical 51-millimeter-diameter tube (fig. 3). The reasons for this difference are not definitely known, but it is probably due to the geometry of the two setups and to the presence of the relatively massive aluminum rotor in the apparatus for turbulent studies.

SUMMARY OF RESULTS

From a preliminary investigation of the effects of geometrical configuration and one type of turbulence on the pressure-inflammability limits of propane-air mixtures, the following results were obtained:

1. Experiments in five flame tubes of 18- to 51-millimeter diameter showed that the mixture-composition range of inflammability narrows and the minimum pressure for flame propagation increases with diminishing tube diameter.
2. For a quiescent mixture of a given composition, the effect of configuration on the pressure limit was found to be a wall effect, because the limit was found to depend directly upon relative wall area as expressed by the surface-volume ratio.
3. Experiments with turbulent mixtures in which the chief motion of the mixtures was directed toward the walls showed the same qualitative effect upon range of inflammability and minimum pressure for flame propagation that was observed when the relative wall area was increased for quiescent mixtures by burning the mixtures in tubes of smaller diameters.

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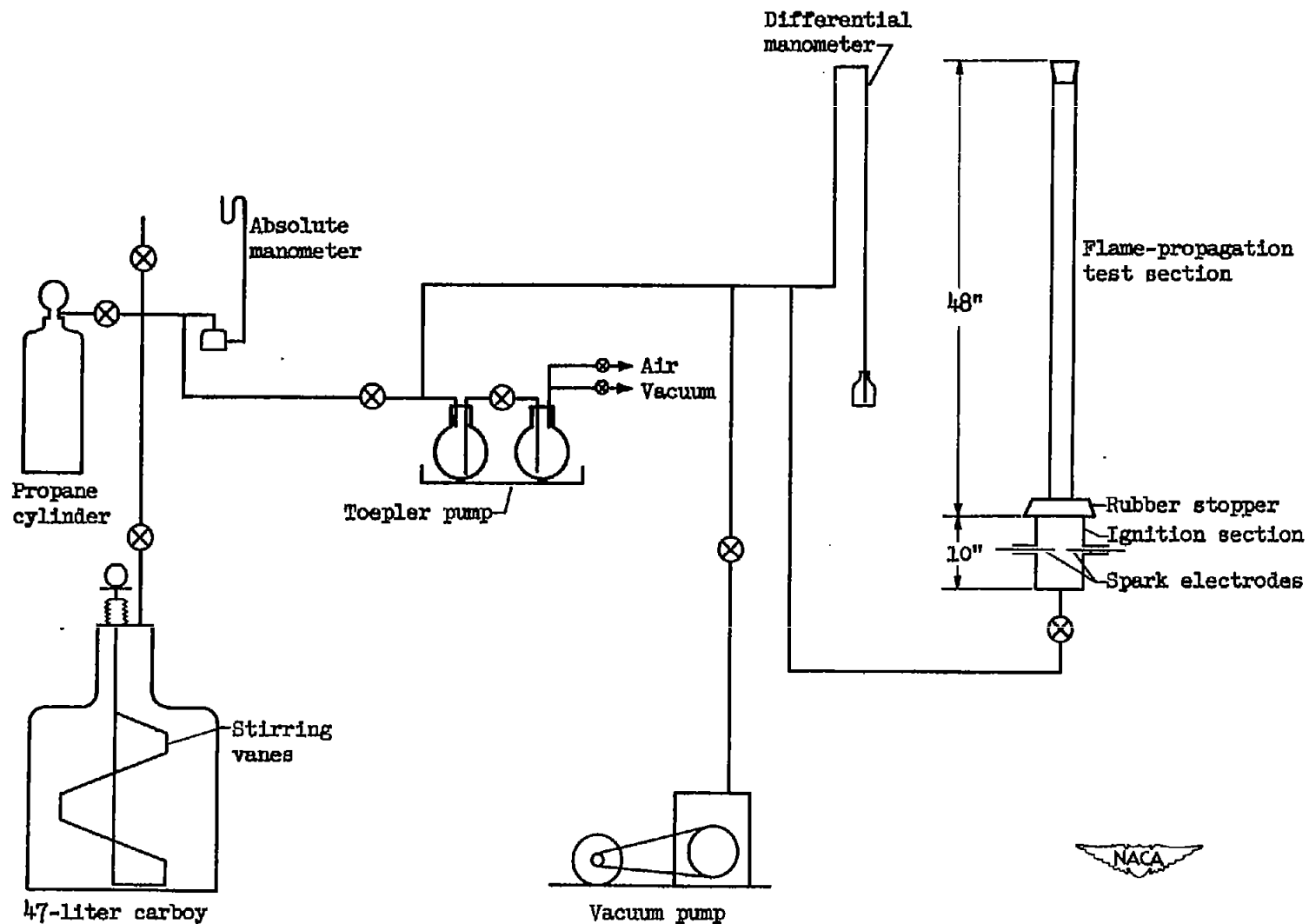


Figure 1. - Apparatus for measuring pressure-inflammability limits of quiescent propane-air mixtures.

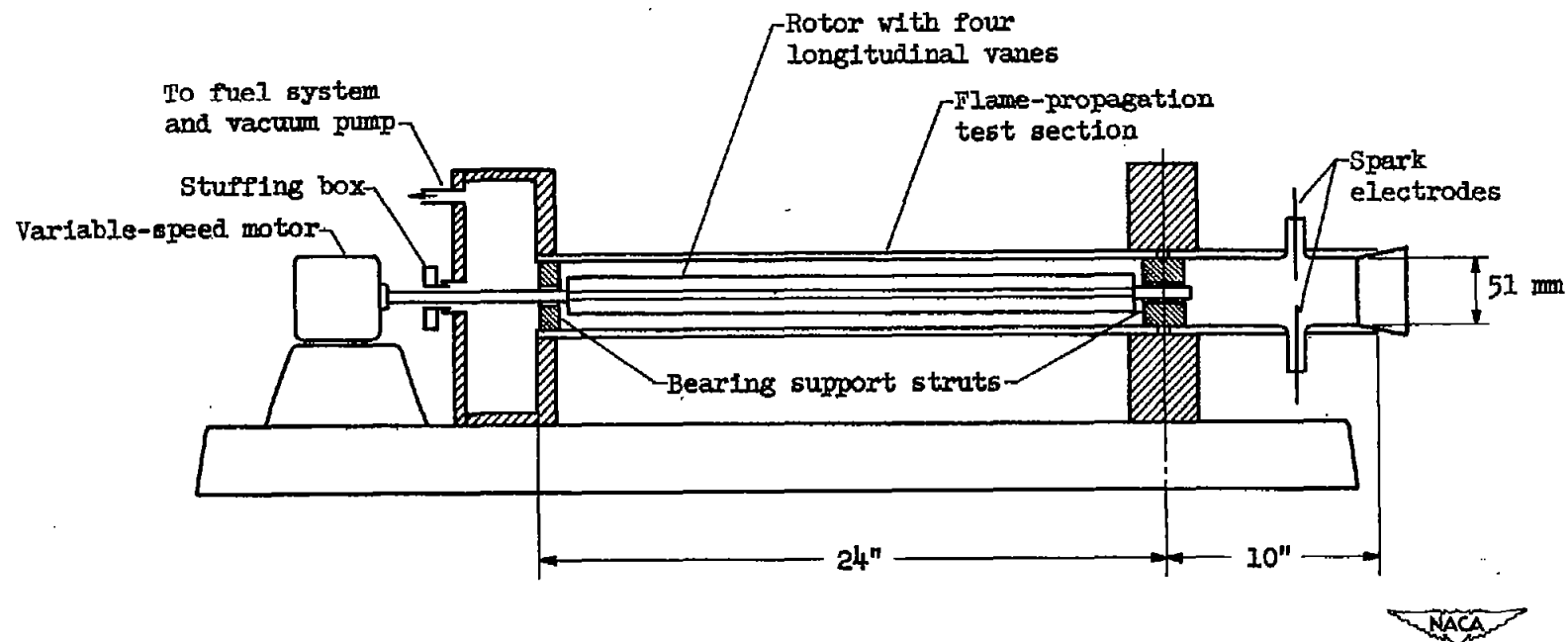


Figure 2. - Apparatus for measuring pressure-inflammability limits of turbulent propane-air mixtures.

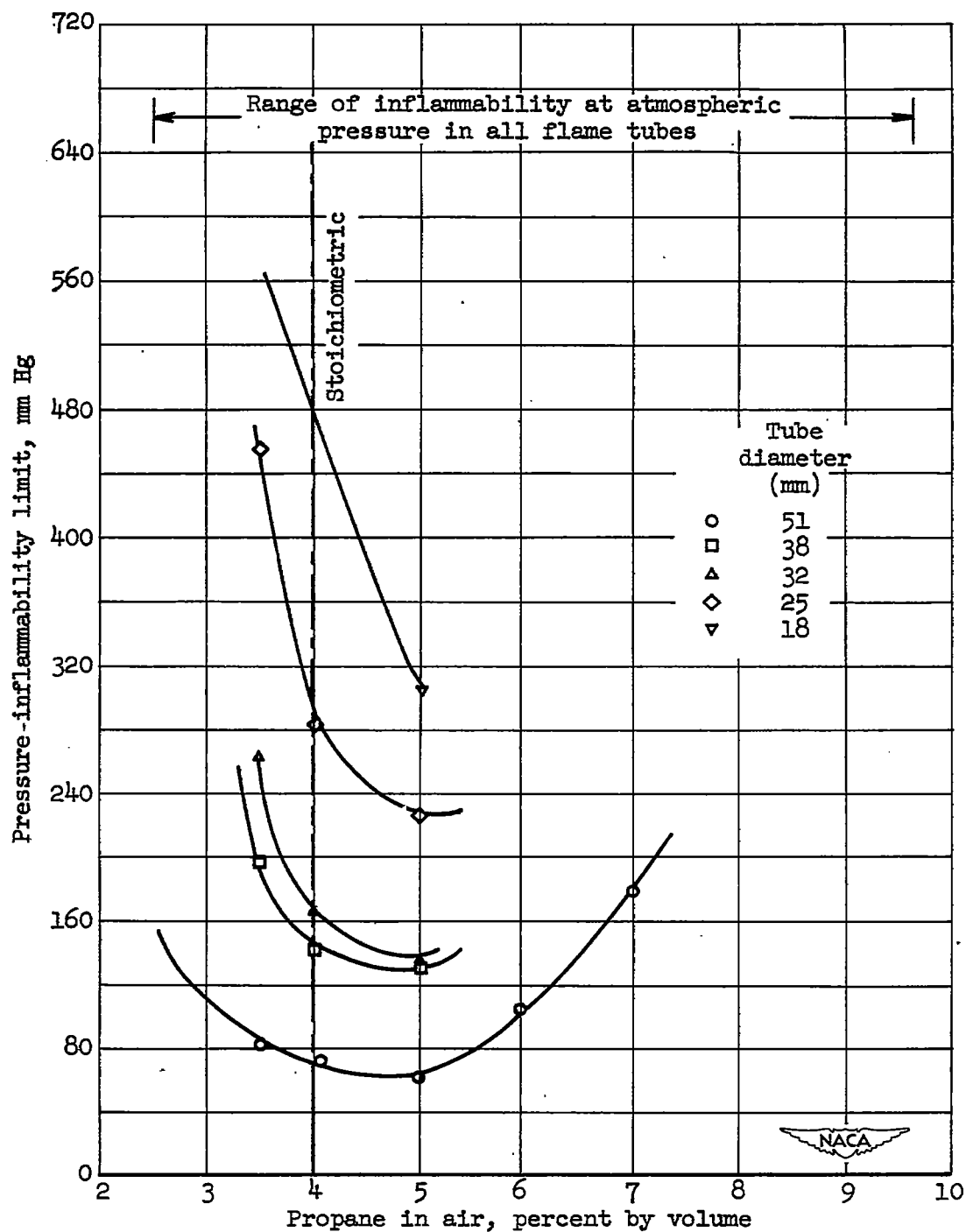


Figure 3. - Effect of tube diameter on pressure-inflammability limit.

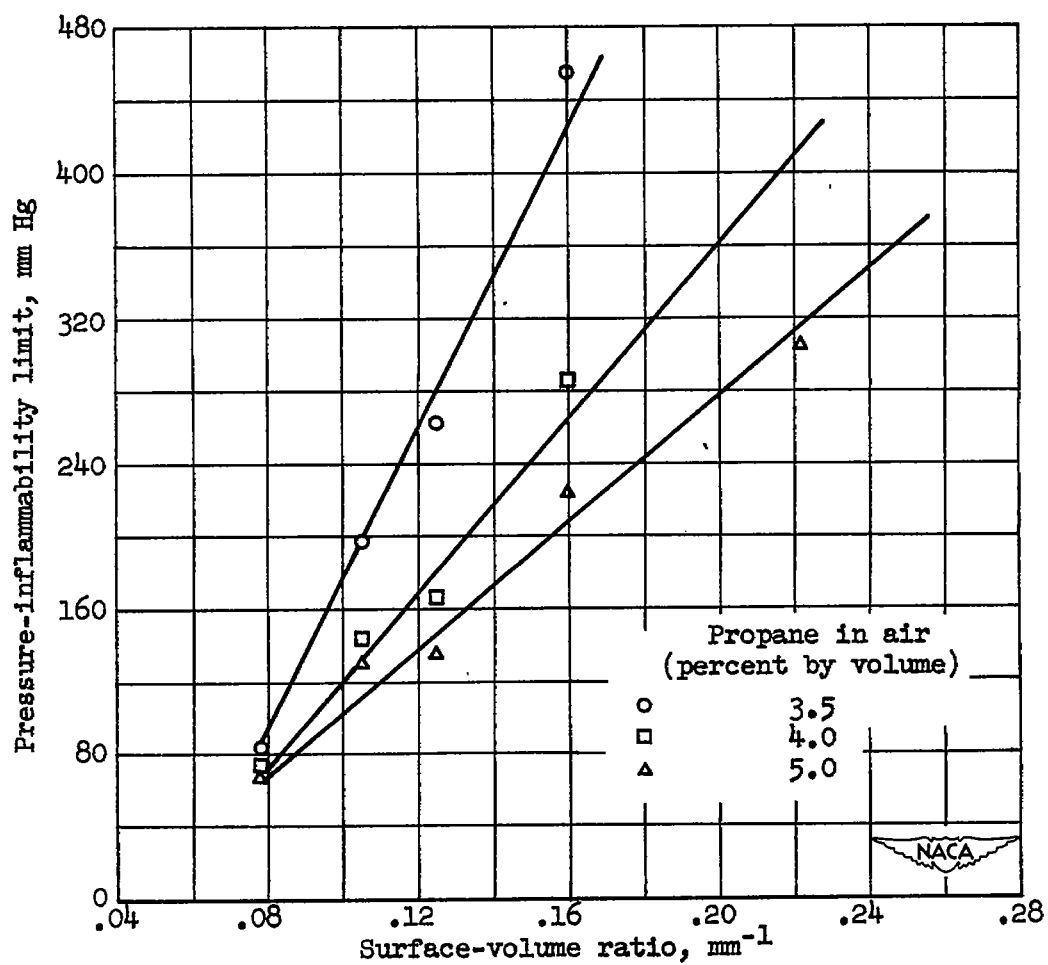


Figure 4. - Relation of pressure limit to surface-volume ratio.

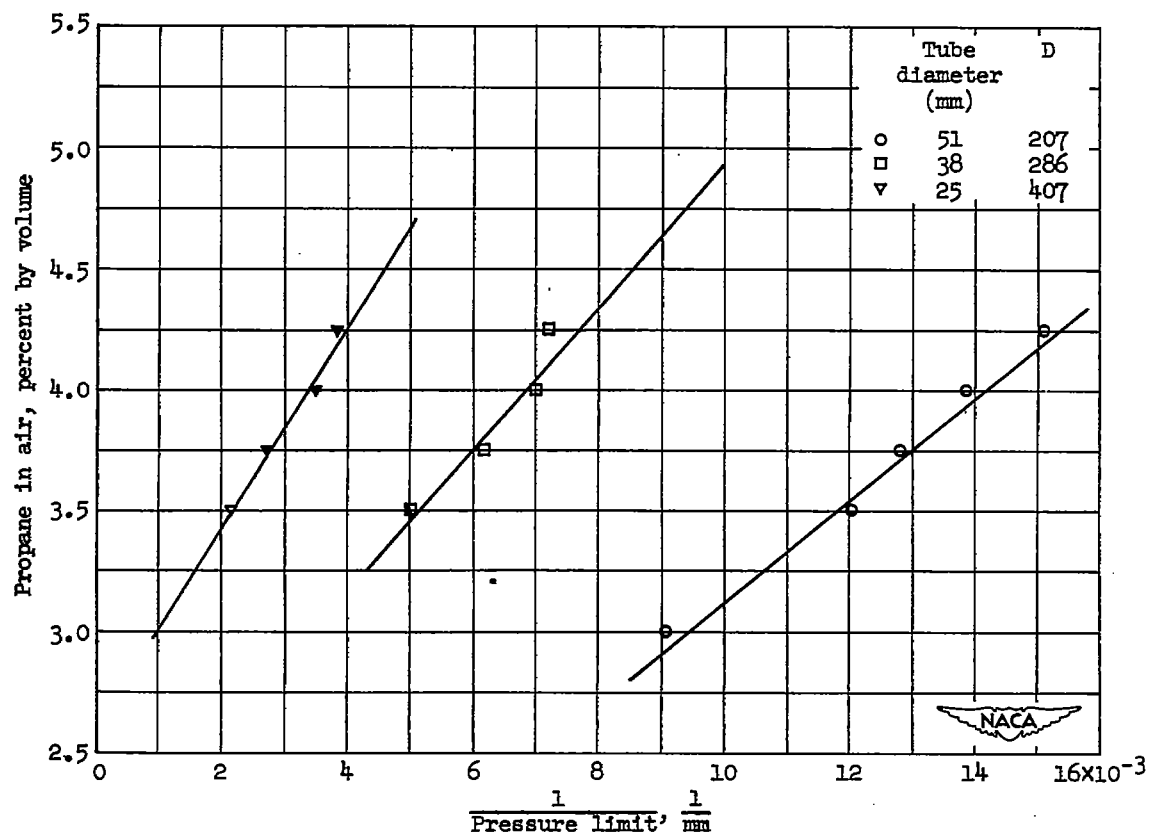


Figure 5. - Propane concentration against reciprocal pressure limit by method of reference 5.

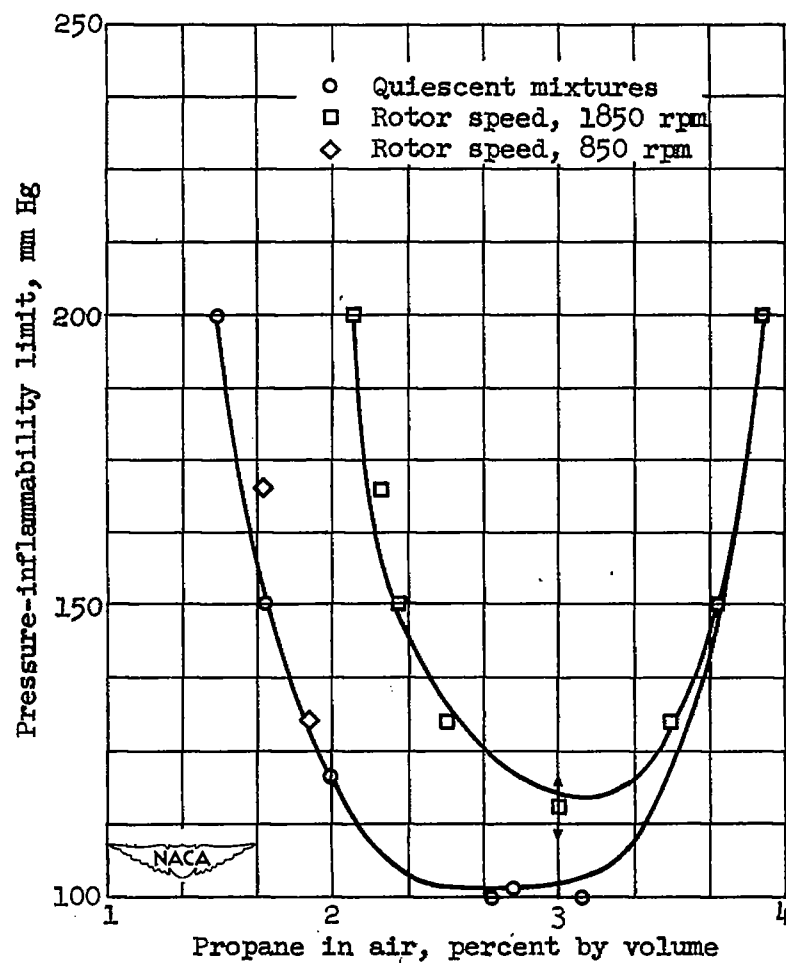


Figure 6. - Effect of turbulence on pressure-inflammability limit.